GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: 8/10/78

Project Title: Theoretical and Experimental Study of the Thermal Stability of Soils

Project No: E-25-608

Co-Project Directors: Dr. William Z. Black and Dr. James G. Hartley

Sponsor: National Science Foundation

Agreement Period: From 8/15/78 Until 1/31/~~80~~ 81
(Grant Period -- Includes flexibility period)

Type Agreement: Grant No. ENG 78-09244, dated 8/2/78

Amount:
$38,192 NSF
2,516 GIT (E-25-344)
$40,708

Reports Required: Annual Progress Report (if 2nd increment of funding is awarded); Final Project Report

Sponsor Contact Person (s):

Technical Matters

(Program Officer)
Dr. Win Aung
Program Director
Heat Transfer Program
Division of Engineering
National Science Foundation
Washington, D.C. 20550
Phone: (202) 632-5867

Contractual Matters
(thru OCA)

Ms. Mary Frances O'Connell
Grants Manager
MPE/BBS/SE Branch
Division of Grants and Contracts
National Science Foundation
Washington, D.C. 20550
Phone: (202) 632-2858

Defense Priority Rating: N/A

Assigned to: Mechanical Engineering (School/Laboratory)

COPIES TO:

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Other

CA-3 (3/76)

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: 5/15/81

Project Title: Theoretical and Experimental Study of the Thermal Stability of Soils

Project No: E-25-608

Project Director: Dr. W. Z. Black & Dr. J. G. Hartley

Sponsor: National Science Foundation

Effective Termination Date: 1/31/81

Clearance of Accounting Charges: 1/31/81

Grant/Contract Closeout Actions Remaining:

_ Final Invoice and Closing Documents

x Final Fiscal Report (Financial Accounting (FCTR)

_ Final Report of Inventions

_ Govt. Property Inventory & Related Certificate

_ Classified Material Certificate

_ Other ____________________

Assigned to: Mechanical Engineering (School/~~Laboratory~~)

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Project Code (GTRI)
Other ____________________

CA-4 (1/79)

E-25-608

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I–PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
Georgia Institute of Technology, Atlanta, Georgia 30332	Heat Transfer Program	ENG 78-09244
	4. Award Period: From 8/15/78 To 1/31/81	5. Cumulative Award Amount: $81,242

6. Project Title
Theoretical and Experimental Study of the Thermal Stability of Soils

PART II–SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

Thermal instability occurs in a moist, porous medium as a result of significant drying due to excessive thermally induced moisture movement. When a cylindrical heat source is embedded in a moist soil, the soil adjacent to the heat source is predicted to dry in two distinct stages. Earlier analytical work at Georgia Tech showed that the first stage of drying is associated with a drying rate which generally decreases until a critical moisture content is reached. Thereafter the drying rate generally increases until complete drying of the soil in the vicinity of the heat source has occurred.

The primary objectives of this investigation were to characterize the thermal stability of a soil through experimental measurements, to validate the predictions of the analytical thermal stability model, and to expand the analytical model in order to investigate the movement of the drying front as it propagates away from the heat source. Thermal stability measurements are made on recompacted soil samples with a thermal probe similar to the type commonly used for the determination of thermal conductivity. A thermal stability limit, in the form of a critical Fourier number, is defined based on the time at which the critical moisture content is attained in the soil adjacent to the heat source. Computer simulations, using experimentally determined thermal and hydraulic properties, were performed and compared to the results of the thermal stability tests.

The results of this investigation have shown that:

(a) The factors which determine the thermal stability limits of a given soil of fixed density are the initial moisture content and the heat input per unit length of the cylindrical heat source.

(b) Thermal stability limits for a soil can be correlated for heat sources of different radii having the same heat input per unit length by plotting the critical Fourier number as a function of heat input per unit length. A family of curves are obtained when the initial moisture content is varied.

(c) Thermal stability limits can be determined experimentally using a thermal probe. These measurements are reliable and repeatable if the proper experimental

(Continued on attached sheet)

PART III–TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (√)	Approx. Date
a. Abstracts of Theses		X			
b. Publication Citations		X		X	8/81;11/81
c. Data on Scientific Collaborators		X			
d. Information on Inventions					
e. Technical Description of Project and Results		X			
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
W. Z. Black, Professor J. G. Hartley, Assistant Profess[or]	Wm. Z. Black J. G. Hartley	24 Apr. '81

procedure is used.

(d) The movement of the dry zone in the soil is not a moving front problem in the classical sense.

An experimental procedure has been developed for detailed investigation of this phenomenon and the analytical model has been expanded to account for this movement.

ABSTRACTS OF THESES

Abstracts of the following theses are attached:

1. "Heat and Mass Transfer in a Semi-Infinite Moist Soil with a Drying Front Present", proposed Ph.D. Thesis, R. J. Couvillion.

2. "An Experimental Investigation of the Thermal Stability of Soils Subjected to a Constant Heat Transfer Rate", Proposed M.S. Thesis, B. C. Drew.

3. "Energy Conservation in Underground Building Through Use of Insulating Materials", M.S. Thesis, J. M. Manson.

HEAT AND MASS TRANSFER IN A SEMI-INFINITE MOIST SOIL WITH A DRYING FRONT PRESENT

by

R. J. Couvillion
Ph.D. Graduate Student
School of Mechanical Engineering
Georgia Institute of Technology

PROPOSAL ABSTRACT

This thesis will be an analytical and experimental investigation of the propagation of a drying front into a moist soil. The system to be studies is a semi-infinite, homogeneous, isotropic moist soil with an impermeable heat source at the boundary. The heat flux or temperature will be specified as a function of time at the boundary. Initial moisture content, pressure, and temperature distributions will also be specified.

Governing equations for the coupled heat, moisture, and air transfer will be written and non-dimensionalized to determine dominant dimensionless groups. Numerical solutions for temperature, moisture distribution, pressure distribution, and drying front position as functions of time will be obtained. The possibility of the front reaching a steady state position will be explored. The factors most important in describing drying front movement will be determined from the solutions.

An experiment will be designed to measure temperature distribution and monitor front location. If convenient moisture measurement techniques are discovered, moisture content distributions will also be measured.

AN EXPERIMENTAL INVESTIGATION OF THE THERMAL STABILITY OF SOILS SUBJECTED TO A CONSTANT HEAT TRANSFER RATE

BY

B. C. Drew
Graduate Student, M.S. Candidate
Analytical Engineer
Environmental and Space Systems
Hamilton Standard (Connecticut)

ABSTRACT

This thesis presents the results of an experimental investigation of the thermal stability of soils subjected to a cylindrical heat source with a constant heat transfer rate per unit length. The experimental measurements are derived from the response of a "thermal conductivity probe". Accurate experimental data of the thermal conductivity and the thermal stability of a native soil are presented. The work validates an analytical model of thermal stability and results indicate that the critical parameters involved in determining the thermal stability of moist soils are the density and initial moisture content of the soil, the heat transfer rate and the Fourier number. The influence of thermal stability limits on probe measurements of thermal conductivity is also discussed.

ENERGY CONSERVATION IN UNDERGROUND BUILDINGS THROUGH USE OF INSULATING MATERIALS

by

J. M. Manson
Graduate Student, Completed M.S.
Engineer
Aramco, (Saudi Arabia)

ABSTRACT

The area of energy conservation in underground buildings has been somewhat neglected in the past. Most emphasis has been placed on conserving energy in the above-ground living space. Significant amounts of energy can be conserved by placing insulation on the underground portions of buildings.

This thesis studies the practicality of reducing energy consumption in underground buildings by placing insulating materials in the soil or by applying insulation to the exterior portion of the building.

The heat transfer analysis used in this study is a steady-state, two-dimensional finite element computer program. The program calculates the heat transfer rate from a building that is maintained at a fixed temperature. Two dissimilar locations were selected as extreme cases representing cold and hot regions of the United States. Madison, Wisconsin was chosen as a city where an underground building would experience a severe heating load. For a city where the structure would have excessive cooling loads, El Paso, Texas was used. At both locations the monthly air temperatures, soil temperature profiles and solar heat fluxes were tabulated for use in input to the program.

The computer program was used to calculate the temperature distribution in the soil and ultimately the heat transfer rate from the building. This rate of heat transfer was converted into a cost of energy using estimated prices for typical heating fuels.

The thickness and type of insulation was varied to determine the best combination for potential energy savings. A brief economic feasibility study was completed to determine the practicality of conserving energy through the use of insulation materials with the underground buildings. Considerable net monetary savings can be achieved by installing small amounts of low conductivity man-made insulations such as polystyrene. Comparable net savings can be realized by installing larger amounts of inexpensive higher thermal conductivity insulators such as dry sand. Potential exists for additional research into producing and testing higher conductivity insulating materials. This potential will become greater if fuel prices continue to increase faster than insulation costs.

PUBLICATIONS

A. The following publications are based all or in part on the information/findings generated by this project.

1. Hartley, J. G. and Black, W. Z., "Transient Simultaneous Heat and Mass Transfer in Moist, Unsaturated Soils", accepted for publication in ASME J. Heat Transfer, August, 1981, and for presentation at 20th ASME/AIChE Heat Transfer Conference, August 1981.

2. Drew, B. C. and Hartley, J. G., "An Experimental Investigation of the Thermal Stability of Soils Subjected to a Constant Heat Transfer Rate", submitted for presentation at 1981 ASME Winter Annual Meeting, November, 1981.

3. Black, W. Z., Hartley, J. G. and Manson, J. M., "Energy Conservation in Underground Buildings by Means of Exterior Insulation", submitted for presentation at 1981 ASME Winter Annual Meeting, November, 1981.

4. Couvillion, R. J. and Hartley, J. G., "Heat and Mass Transfer in a Semi-Infinite Moist Soil with a Drying Front Present", to be submitted to ASME J. Heat Transfer, 1981.

B. The following publications by the principal investigators relating to heat transfer in soils and soil thermal stability were also written during the period of this report.

1. K. E. Saleeby, W. Z. Black, and J. G. Hartley, "Effective Thermal Resistivity for Power Cables Buried in Thermal Backfill", IEEE Trans. on Power Apparatus and Systems, VOL. PAS-98, No. 6, November/December 1979.

2. R. A. Bush, W. Z. Black, and M. A. Martin, Jr., "Soil Thermal Properties and Their Effect on Thermal Stability and the Rating of Underground Power Cables", published in the Proceedings and presented at the 7th IEEE/PES Conference and Exposition on Transmission and Distribution, Atlanta, Georgia, April 1979.

3. J. G. Hartley and W. Z. Black, "Predicting Thermal Stability and Transient Response of Soils Adjacent to Underground Power Cables", published in the Proceedings and Presented at the 7th IEEE/PES Conference and Exposition on Transmission and Distribution, Atlanta, Georgia, April, 1979.

4. Martin, M. A., Black, W. Z., Bush, R. A. and Hartley, J. G., "Practical Aspects of Applying Soil Thermal Stability Measurements to the Rating of Underground Power Cables", accepted for publication in IEEE Trans. on Power Apparatus and Systems, and presented at IEEE/PES Winter Meeting, Atlanta, February 1981.

SCIENTIFIC COLLABORATORS

1. W. Z. Black, Professor, Co-Principal Investigator
   School of Mechanical Engineering, Georgia Institute
   of Technology, Atlanta, Georgia.

2. J. G. Hartley, Assistant Professor, Co-Principal Investigator
   School of Mechanical Engineering, Georgia Institute
   of Technology, Atlanta, Georgia.

3. R. J. Couvillion, Graduate Student, Ph.D. Candidate
   School of Mechanical Engineering, Georgia Institute
   of Technology, Atlanta, Georgia.

4. B. C. Drew, Graduate Student, M.S. Candidate,
   Analytical Engineer, Environmental and Space Systems,
   Hamilton Standard (Connecticut).

5. J. M. Manson, Graduate Student, Completed M.S.
   Engineer, Aramco, (Saudi Arabia).

TECHNICAL SUMMARY

Thermal instability occurs in a moist, porous medium as a result of significant drying due to excessive thermally induced moisture movement. When a cylindrical heat source is embedded in a moist soil, the soil adjacent to the heat source is predicted to dry in two distinct stages. Earlier analytical work at Georgia Tech showed that the first stage of drying is associated with a drying rate which generally decreases until a critical moisture content is reached. Thereafter the drying rate generally increases until complete drying of the soil in the vicinity of the heat source has occurred.

The primary objectives of this investigation were to characterize the thermal stability of a soil through experimental measurements, to validate the predictions of the analytical thermal stability model, and to expand the analytical model in order to investigate the movement of the drying front as it propagates away from the heat source. Thermal stability measurements are made on recompacted soil samples with a thermal probe similar to the type commonly used for the determination of thermal conductivity. A thermal stability limit, in the form of a critical Fourier number, is defined based on the time at which the critical moisture content is attained in the soil adjacent to the heat source. Computer simulations, using experimentally determined thermal and hydraulic properties, were performed and compared to the results of the thermal stability tests.

A previously developed computer program based on the finite difference method was used initially to predict transient temperature and moisture content distributions in a sandy silt (1280 kg/m^3 dry density). In addition a finite element (FE) program has been developed for the solution of two-dimensional, simultaneous heat and mass transfer problems. This program provides much greater flexibility, and the accuracy of the FE results has been checked with exact solutions, published experimental data, and current experimental data. The FE program has been used to predict transient temperature and moisture content profiles in the soil adjacent to a cylindrical heat source, to examine the drying characteristics of the soil, and to develop stability criteria (critical moisture content and critical heat input values) for the sandy silt and C-109 Ottawa sand. These numerical predictions have also been used to correlate the results of the experimental measurements of thermal stability.

The capabilities of the computer programs have also been expanded to account for the presence of a drying front which propagates into the soil. Furthermore, a fully instrumented test cell has been constructed which permits experimental determination of the location of the drying front and verification of the analytical model. This work is part of the experimental and analytical study of the drying of porous materials undertaken by R. J. Couvillion, a Ph.D. student employed under this grant. Mr. Couvillion is expected to complete his degree requirements in August, 1981.

The results of the numerical simulations have shown that thermal stability criteria (i.e. a critical heat input per unit length and a critical moisture content) can be developed and predicted for the soil being investigated. Verification of the validity of the stability criteria has been achieved with small-scale laboratory tests using a thermal probe. In conjunction with this work a microprocessor-controlled instrument for the determination of soil thermal conductivity and the analysis of thermal stability has been designed and constructed. This instrument has been used extensively for thermal stability measurements.

Thermal conductivity measurements have been made with the thermal probe on numerous soil samples for a range of moisture contents and dry densities. Using the instrument described above thermal conductivity measurements on porous samples can be obtained with an accuracy and repeatability of about five percent.

Soil suction data has also been collected over a wide range of pressures for C-109 Ottawa sand and the sandy silt. Initial difficulties associated with preparation of identical samples were overcome with the development of alternative measurement techniques. In addition, a detailed study of the effect of soil additives on thermal conductivity and stability has been undertaken. Candidate additives were selected and evaluated experimentally via thermal conductivity measurements and examination of their effect on the soil microstructure.

John Manson, an M.S. candidate, completed his master's thesis during the period of this grant. His thesis investigated the use of treated soil for the purpose of conserving energy from underground buildings. For these applications soil additives were selected that will reduce the natural soil conductivity and thereby reduce heat flow from the underground portion of the building. Detailed heat transfer calculations identified an optimum insulation thickness which will provide maximum net energy savings; using less insulation than the optimum thickness will result in increased energy losses while insulation thickness in excess of the optimum value will save less in energy costs than the additional expense of installing more insulation. The optimum insulation thickness is shown to increase as the thermal conductivity of the insulation increases. Also the potential for energy savings is practically independent of the thermal conductivity of the insulation.

The results of this investigation have shown that:

a. The factors which determine the thermal stability limits of a given soil of fixed density are the initial moisture content and the heat input per unit length of the cylindrical heat source.

b. Thermal stability limits for a soil can be correlated for heat sources of different radii having the same heat input per unit length by plotting the critical Fourier number as a function of heat input per unit length. A family of curves are obtained when the initial moisture content is varied.

c. Thermal stability limits can be determined experimentally using a thermal probe. These measurements are reliable and repeatable if the proper experimental procedure is used.

d. The movement of the dry zone in the soil is not a moving front problem in the classical sense.